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NAVAL AIR ENGINEERING CENTER

REPORT NAEC-92-151

LAKEHURST, N.J.
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FAILURE PROGRESSION MONITORING OF GREASE LUBRICATED TAPERED ROLLER BEARINGS BY WEAR DEBRIS ANALYSIS

Advanced Technology Office
Support Equipment Engineering Department
Naval Air Engineering Center
Lakehurst, New Jersey 08733

27 JULY 1982

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FAILURE PROGRESSION MONITORING OF GREASE LUBRICATED TAPERED ROLLER BEARINGS BY WEAR DEBRIS ANALYSIS

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This report documents a study of the wear debris characteristics of grease-lubricated tapered roller bearings. Bearings were operated to failure in a grease-lubricated environment. Samples of grease were periodically taken and Ferrographically analyzed. The analysis was correlated to actual bearing condition through periodic inspection. Particle morphologies were indicative of bearing distress while quantitative data exhibited no characteristic patterns.

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SUMMARY

The purpose of this program was to experimentally investigate criteria relating the characteristic failure progression of grease-lubricated tapered roller bearings to the quantity and morphology of wear debris in grease samples extracted from the bearings. The testing, sample removal, and optical and scanning electron microscope examination of the bearing surface were performed by SKF Industries, Inc., and are the subject of this report. The debris analysis using the Ferrography method was performed by the Naval Air Engineering Center (NAVAIRENGCEN), Lakehurst, New Jersey, and will be discussed in a separate report to be issued by the NAVAIRENGCEN.

Two sets of two LM102949/LM102910 tapered roller bearings were tested and inspected for failure identification. All testing was sustained until one of the following occurred: (a) a failure of both bearings of a set was experienced as indicated by an increase in bearing vibration level, (b) a lubrication initiated failure was experienced as indicated by the Temperature Rate of Increase Monitor (TRIM), or (c) a bearing life of 100 million inner ring (cone) revolutions was achieved without apparent failure.

The schedule for removing grease samples and inspecting the bearing was different for each set. The testing of Set I bearings was interrupted to remove grease samples after operating for 5, 25, 50, and 100 million revolutions and/or after failure. The bearings were not inspected until test termination. The testing of Set II bearings had scheduled interruptions for both complete grease removal and bearing inspection at the same operating periods specified for Set I bearings.

The testing conditions consisted of the following:

Test Rig...............SKF Industries' R2 endurance testers

Test Bearing...........SKF LM102949/LM102910 tapered roller bearings

Lubrication............Exxon Ronex MP (full charge)

Load (Pounds)..........2,822 radial, 1,280 axial (5,100 equivalent)

Theoretical Bearing
L_{10} Life...............10 million revolutions

Test Speed.............Inner ring (cone) rotation at 800 rpm

Test Time Up...........100 million revolutions - 2,083 hours

Bearing Material.......AISI 4118 steel

Cage Material..........AISI 1010 steel

The testing, grease sample removal, and bearing inspection were successfully completed. Two bearings failed due to spalling and two bearings reached test time up. In addition, the testing of a fifth bearing (bearing 09), used to replace the first bearing that failed, was terminated after 55.6 million revolutions without a failure.

The grease samples were analyzed by Analytical Ferrography and morphology of wear debris was correlated to the surface wear condition of the bearing.

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I. INTRODUCTION

A. The unexpected catastrophic failure of rolling bearings in service can precipitate a chain of events which endanger life, restrict the immediate availability of equipment, and incur excessive expense. In order to prevent unexpected failures, preventative maintenance programs are generally established to check critical components at regular intervals and to replace those components considered on the basis of experience to be likely to fail within the next overhaul period.

B. The long-range objective of this experimental program was to investigate means by which the incidence of unexpected tapered roller bearing failures can be reduced in the field by monitoring the debris content of the grease. In this manner, the extent of the damage to tapered roller bearing parts could be established without completely disassembling the equipment, and bearing replacements could be completed when necessary rather than on a fixed periodic schedule. Such a monitoring method would significantly increase equipment reliability, increase equipment availability by reducing the number of required overhauls, and produce a sizable reduction in recurring maintenance costs. It is also known that bearings can be damaged during disassembly and assembly operations during an overhaul. By reducing the overhaul frequency, the danger of causing handling damage will be reduced, thus further increasing the reliability of the bearings.

C. In a grease-lubricated bearing, there are three primary conditions in which a bearing failure can occur:

1. Contamination of the bearing by foreign material which can result in corrosion and/or heavy debris denting of the components. Both corrosion and denting can greatly affect the service life of the bearing. The effect of debris denting was dramatically shown in a prior test program performed for the Navy (reference (a)), where ball bearings in 3 um filtered oil ran 40 times the calculated L_{10} life.

2. Inadequate or marginal lubrication resulting from the depletion of the grease, or the inability of the oil in the grease to bleed into the bearing contact areas at a sufficient rate. Inadequate or marginal bearing lubrication results in a higher operating temperature and a greatly accelerated wear rate produced by the greater metal-to-metal contact and increased friction. This condition, if allowed to exist, will produce failures due to surface initiated spalls or a thermal imbalance condition between the rings which will cause the bearing to seize.

Ref: (a) Dalal, H. M., et al. "Progression of Surface Damage and Oil Wear Debris Accumulation in Rolling Contact Fatigue", Naval Air Engineering Center, Final Report on Contract No. N00156-74-C-1634, SKF Report AL75T007 (1975)

3. Classical fatigue spalling which results from the cycle loading of the bearing elements. It is the method of failure upon which the theoretical L_{10} life of a bearing is based.

D. This program was designed to obtain data on one possible method of detecting the initiation of greased tapered roller bearing failure condition by the monitoring of grease samples for retained wear debris. In this manner, background data would be accumulated which could be utilized to develop criteria for the prediction of the initiation of bearing failures.

E. To accomplish these goals, the program consisted of testing two pairs of grease-lubricated tapered roller bearings. The first set was run to a time-up life of 100 million revolutions (MREV) or until a grease or bearing failure occurred. Grease samples were periodically removed during the testing for wear debris content analysis. The second set of bearings was degreased, disassembled, inspected, and regreased periodically throughout the test in order to correlate wear debris with progressive bearing surface damage. The grease samples were analyzed by means of Analytical Ferrography.

II. EQUIPMENT AND TEST PROCEDURE

A. TEST MACHINE

1. All testing was conducted using SKF-developed R2-type bearing endurance testers. A general drawing of the overall tester is presented in Figure 1, and a detailed drawing of one of the test heads is presented in Figure 2. Each machine is comprised of a symmetrical horizontal arbor supported on two cylindrical roller load bearings which in turn are supported in split main housings. Labyrinth seals are located on both sides of the load bearings to minimize the escape of the recirculating oil supplied to the bearings for lubrication and cooling. Two test tapered roller bearings (LM102949/LM102910) are press fit on the arbor, one at each end, and support a top-hat housing which also houses a pilot bearing (NU304 cylindrical roller bearing). The pilot bearing maintains the alignment of the test bearings. The thrust or axial load is applied by clamping two load beams, one on each end, against the top-hat housings. This load is applied through balls positioned in cone-shaped holes in the center of the top-hat housings and the load is determined by strain gauges on one load beam. The radial load to each bearing is applied by a deadweight lever arm, which is attached to the top-hat flange through a pin at the centerline of the test bearing.

2. The test shaft is belt driven by a 15-HP, constant-speed AC motor through pulleys selected to provide the desired test speed. The load bearings are splash lubricated with oil supplied from a central recirculating system at a rate sufficient to maintain the bearing operating temperature below 398°K. The recirculating oil system contains a 25-micron full flow filter.

3. The test bearing outer ring operating temperatures are sensed by shielded thermocouples monitored by a Data General Nova mini-computer control system which also monitors the axial load. This system constantly scans all of the analog input points, and each point is examined at a minimum rate of once every two seconds. The computer is programmed to turn the drive motor off whenever the temperature or rate of temperature increase exceeds preestablished values, or when the thrust exceeds established limits. In addition, the test bearing temperature measured at each 12-minute interval is stored in the computer and printed out at 8-hour intervals to provide a hard copy log of the thermal history of each test bearing.

4. A vibraswitch, attached to the main housing, monitors the general vibration level of the machine and turns off the drive motor when a significant increase, typical of a bearing failure, occurs.

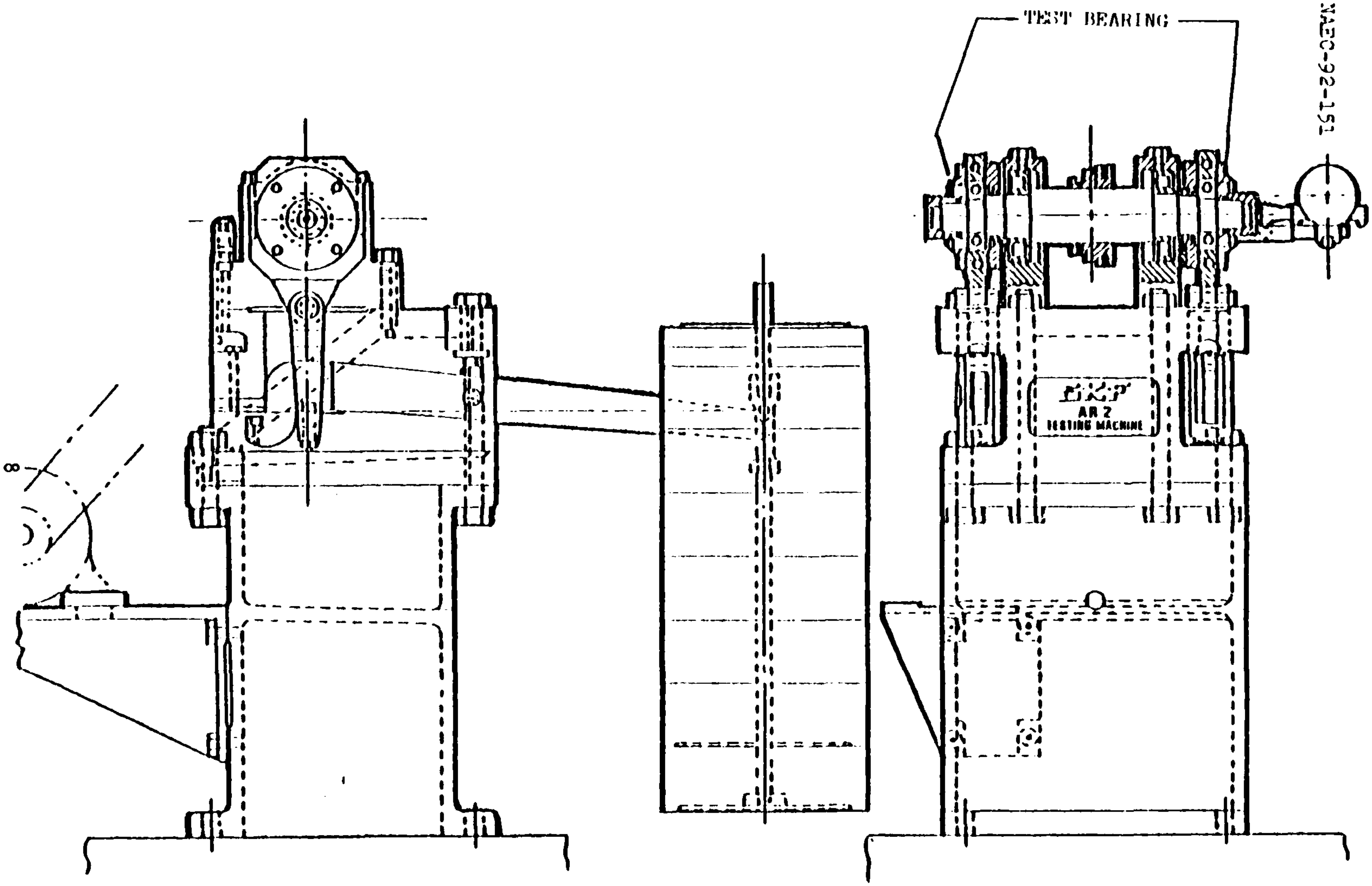

Figure 1. Layout Drawing of R2
Test Rig

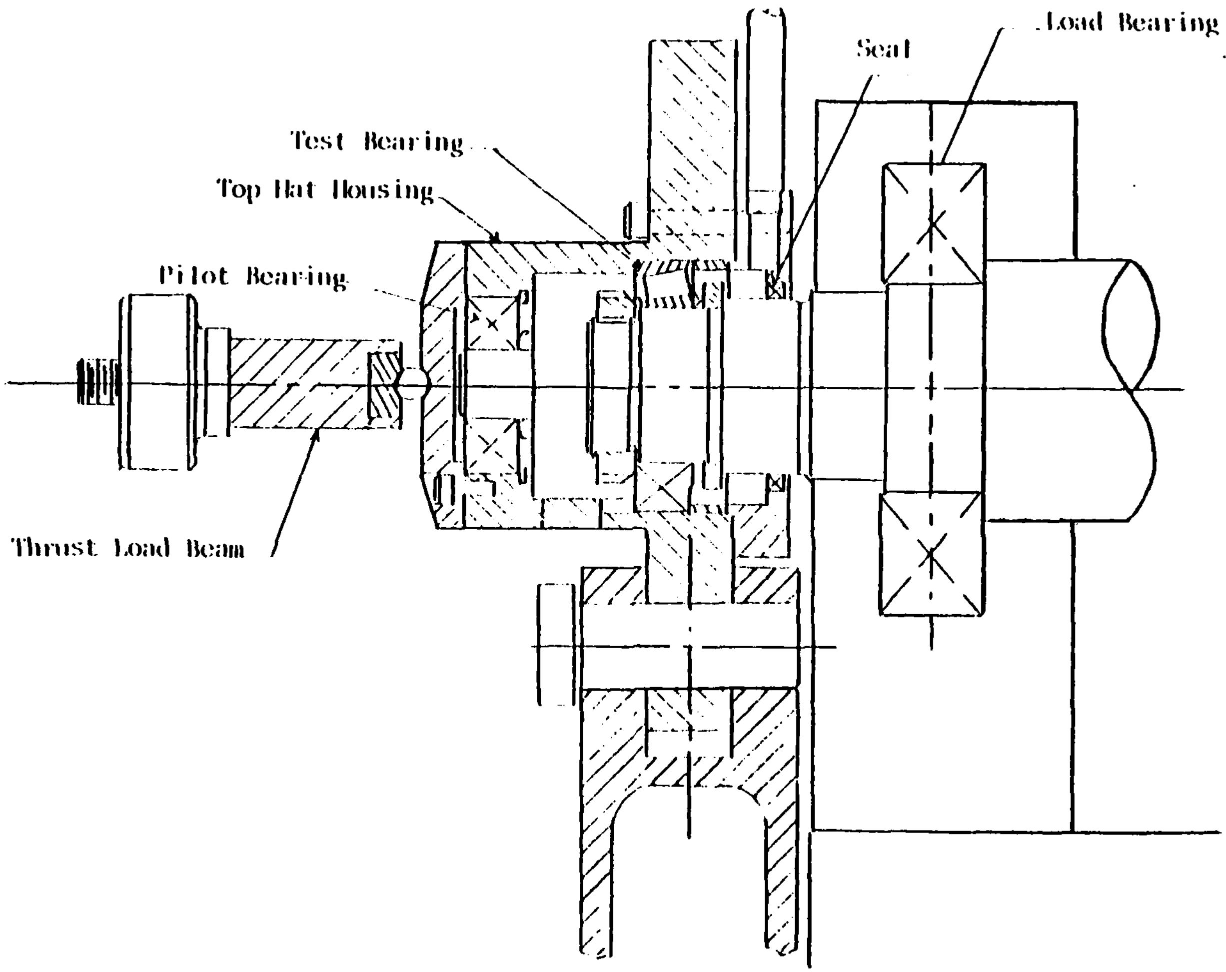

Figure 2. Detailed Drawing of R2 Test Head

B. TESTING AND BEARING PREPARATION AND INSPECTION PROCEDURE. The following procedure was used in preparing and mounting the test bearings, taking grease samples, and inspecting the test bearings. Bearing Set I refers to two bearings numbered 05 and 06 from which grease samples were scheduled for removal at the accumulation of 5, 25, 50, and 100 million inner-ring revolutions. Set II refers to the two bearings numbered 07 and 08 which were removed from the tester, all grease removed, and then the contacting surfaces of the bearings inspected at intervals specified for bearing Set I.

1. INITIAL MARKING AND CLEANING OF BEARINGS

a. All test bearings (LM102949 [cone] /LM102910 [cup]) were manufactured from AISI 4118 steel which was case hardened to a depth of 0.6 to 0.9 mm. The cages were stamped from AISI 1010 steel. The bearings were disassembled and the rings (cup and cone) numbered for identification purposes using an electric etching pencil. The small diameter flange was removed from the cone to permit easy assembly and disassmebly.

b. The inner and outer rings (cups and cones), and cage and roller sets of Set I bearings were also marked with an electric etching pencil. Eight equal segments were etched to permit identification of areas from which to remove grease during progressive sampling.

c. Each bearing was assembled and placed in a horizontal position in a glass container partially filled with Dalco DS-50 solvent and ultrasonically cleaned for five minutes. Each bearing was then flushed with petroleum ether and allowed to air dry.

2. GREASING OF BEARINGS

a. Each bearing was given a full charge by filling all voids in the bearing with Exxon Ronex MP grease according to standard practice for tapered roller bearings. This was accomplished by applying with a stainless-steel spatula an even, thick coat of grease on the inner and outer raceways. The rings were assembled with the cage and roller set, forcing the grease to fill all open space within the bearing. Excess grease extending from the sides of the bearing was then removed using the stainless-steel spatula. The bearings were wrapped in coated paper in preparation for assembly into the test rig.

b. The NU304 pilot roller bearings used to maintain proper alignment of the test bearings were also cleaned and greased with Exxon Rone MP grease.

3. ASSEMBLY OF BEARINGS IN RIG

a. Prior to the assembly of the bearings onto the shaft, the shaft bearing seats and surrounding area were washed with Dalco DS-50 solvent and wiped dry with a lint-free rag. The bearings were then pressed onto the shaft, using the specially adapted hydraulic ram which was also cleaned with Dalco DS-50 prior to use. The marked side of the bearing was located on the outboard side of the shaft.

b. The bearing housing, following cleaning with Dalco DS-50, was assembled with the bearing type number on the cup located at the 12 o'clock position.

c. The axial load was applied by tightening the adjustment rods until the desired load of 5,693 N (1,280 pounds) was obtained. The desired radial load of 12,552 N (2,822 pounds) was then applied to each bearing. This was accomplished by calculating the necessary load to be placed on the arm and checking the weights on a spring scale before attaching to the arm.

4. TESTING

a. All testing was performed at an inner ring rotational speed of 800 rpm with a radial load of 12,552 N and a thrust load of 5,693 N. The combined load results in a theoretical bearing L_{10} life of 10 million revolutions (MREV). The outer ring operating temperatures of the test bearings were measured by shielded thermocouples and monitored by a test floor control computer. The computer was programmed to incorporate a subroutine (temperature rate of increase monitor or TRIM) which would automatically stop the drive motor when a temperature increase rate of 1.1°K per minute or greater was experienced for a period sufficient to produce a cumulative increase of 11.7°K, or when an operating temperature greater than 393°K was sensed. In addition, the test bearing temperature, measured each 12-minute interval, was stored in the computer and printed out at 8-hour intervals to provide a hard copy of the thermal history of each bearing. A bearing vibration level monitor was used to shut off the machine due to increases in vibration caused by a bearing failure.

b. Bearing Set I was run under conditions described in a above with the tests interrupted after the accumulation of 5, 25, 50, and 100 MREV for the removal of grease samples.

(1) The testing was sustained until one of the following occurred:

(a) a failure of both bearings was experienced, as indicated by an increase in bearing vibration level and/or audible noise,

(b) a lubricant failure was experienced, as defined by the TRIM, or

(c) a bearing life of 100 million inner ring revolutions was achieved without failure.

(2) The grease samples were removed with a stainless-steel spatula from 45° segments on the outboard and inboard sides of the cage and roller set. The removed grease was replaced with approximately the same quantity of new grease prior to restarting the test. Progressive samples were removed from different segments permitting each sample to contain the debris accumulated during the test period up to the time of sampling.

(3) The two grease samples removed at each shutdown were placed in different segments of a clean glass petri dish marked to identify the location from which it was removed. The petri dish was covered by a glass plate and refrigerated until it was delivered to the NAVAIRENGCEN for analysis.

(4) At the conclusion of the test, two grease samples were removed from the specified areas. The bearings were carefully removed from the rig, using a special puller which was precleaned with Dalco DS-50. The major portion of the remaining grease was then removed. Each bearing was placed in a glass container filled with Dalco DS-50 and ultrasonically cleaned. The cleaning fluid and debris were placed in a glass bottle and sealed with a plastic cap using a teflon sealing disk. The grease and cleaning fluid were refrigerated until delivered for analysis.

(5) The bearings were disassembled and a visual inspection of all elements performed, using an optical microscope with magnification up to 30X. The inner ring surfaces were also examined with a scanning electron microscope (SEM) to further determine the degree of surface microdamage, and photomicrographs were taken for documentation purposes.

c. Bearing Set II was tested in the same manner as Set I except at each shutdown interval, as specified in b above, the bearings were removed and the grease sampling, bearing cleaning, and examination performed in the same manner as that performed at the termination of Set I testing.

III. TEST DISCUSSION AND RESULTS

A. GENERAL DISCUSSION

1. If a rolling contact bearing is correctly manufactured, mounted, lubricated, maintained free of external contamination, and otherwise properly handled, all causes of failure are essentially eliminated except one--fatigue of the material. The life of an individual bearing is defined as the number of revolutions, or hours of operation at a constant speed, which the bearing is capable of running before the first evidence of fatigue develops in the material of either ring or any of the rolling elements.

2. The life of a group of bearings requires a more specific definition because, when a number of identical bearings are run under the same conditions of load and speed, there is a dispersion of their lives.

3. The "rating life" or briefly "life" of a group of bearings is defined by the Anti-Friction Bearing Manufacturing Association (AFBMA) as the number of millions of revolutions at a given speed that 90 percent of the bearings will complete or exceed before the first evidence of fatigue develops. The symbol L_{10} has been designated to represent that group life value. The symbol L_{50} represents the life which 50 percent of a group of bearings will complete or exceed (median life).

4. Extensive testing by SKF and other companies, together with extensive theoretical research, has shown that within a reasonable degree of accuracy, the fatigue life of roller bearings is inversely proportional to the ten thirds (10/3) power of the equivalent load applied to a roller bearing. This relationship between life and load has been adopted by the International Standards Organization. The equivalent load is defined as the magnitude of radial load which would result in the same life as that resulting from the combined radial and thrust loads applied.

5. Thus the equation [$L_{10} = (C/P)^{3.33}$] expresses the rated life of a group of bearings when P is the equivalent applied load and C is the dynamic capacity, that is, that load which will give a life of one million revolutions. The numerical value of C in pounds for a specific bearing size and type is provided in bearing catalogs.

6. In establishing a test program, such as the one reported here, it is important to select an applied load and operating speed, such that bearing failures will occur within a given time frame to minimize testing expenses and still obtain the desired information. Therefore, for this program, the applied loads of 12,552 N radially and 5,693 N axially, which equals an equivalent load 22,685 N for a C/P = 2, were selected which results in a calculated L_{10} life of 10 MREV for the test bearings which had a basic load rating, C, of 45,370 N. A test-time-up period of 100 MREV was selected to insure the fatigue failure of some of the test bearings.

7. An inner ring rotational speed or shaft speed of 800 rpm was chosen to limit the expected outer ring operating temperature to a value which would not impose excessive restrictions on the grease selection. With a test speed of 800 rpm, the test time-up was 2,083 hours.

8. The selection of the grease was based on properties which were compatible with both the test conditions and the analysis techniques used by the NAVAIRENGCEN to separate the debris from the grease. The grease initially selected met MIL-G-23827 specifications, and had been successfully used previously in a NAVAIRENGCEN test program conducted by SKF on grease-lubricated ball bearings (reference (b)). However, preliminary runs with this grease used in tapered roller bearings resulted in samples that could not be dissolved sufficiently to permit the evaluation of the metal debris particles. The greater degradation of the grease in the tapered roller bearing is attributed to the difference in the internal kinematics and working of the grease experienced within the two types of bearings. Therefore, the grease was changed to a commercial product, Exxon Rone MP, which had previously performed well in tapered roller bearings (reference (c)). A check performed by the NAVAIRENGCEN on a sample of the grease indicated that it was compatible with the analysis technique. Ronex MP grease consists of a lithium soap base and a paraffinic mineral oil lubricating fluid.

9. The two basic methods used to detect the initiation of a bearing failure during the testing portion of this program were vibration level monitoring and TRIM. The vibration monitoring is a standard procedure used in bearing endurance testing and is utilized to turn off the drive motor when the vibration level increases to a value representative of that produced by a small spall in one of the bearing elements. The TRIM procedure, a control developed by SKF to detect early warnings of lubrication failures in grease-lubricated bearings, turns off the drive motor when a bearing temperature increase rate is such that a recovery of the bearing grease system would not be expected and, thus, a catastrophic bearing failure would result if the bearing were allowed to continue running for an additional short period of time.

<u>Ref:</u> (b) NAVAIRENGCEN Report NAEC 92-133 of Nov 1978: Failure Progression Monitoring by Wear Debris Analysis in Grease Lubricated Ball Bearings

(c) Ninos N. J., et al; "Performance of Automotive Wheel Bearing Greases", U.S. Army Mobility Equipment Research and Development Command, Final Report on Contract DAAK70-77-C-0034, SKF Report AL78T032, (1978).

10. These two methods of detecting imminent bearing failure, were incorporated in this program to prevent catastrophic failures which would generate excessive debris. This would render the results of the testing meaningless with respect to the desired goal of determining an imminent failure by examining the size, shape, and quantity of bearing generated debris retained in samples of the used grease.

11. Plans were made to remove grease samples from the inner ring, outer ring, and the cage and roller set to permit the determination of the most sensitive location with respect to the generated debris. The quantity of grease removed from each location would also be representative of the amount of grease present and thus could be used to determine if adequate sample sizes would be present at the various locations in an actual application.

12. During the grease sample removal from the Set I bearings, which was performed at selected time intervals without disassembling the bearings, it was established that insufficient grease was available on the cone and cup to obtain a sample. Therefore, only two samples were removed at each sampling period: one from the cage and roller set on the outboard side and one from the cage and roller set on the inboard side. The grease removed from each location was placed in separate compartments of a glass petri dish. Each compartment was marked to indicate the position from which the sample was removed.

13. Of the four bearings tested, two experienced fatigue failures and the other two bearings ran to time-up. No TRIM (or high temperature) shutoffs occurred. Both bearings that failed were from Set I. Bearing 06 failed after 35 MREV and was replaced by bearing 09 so testing could be continued on bearing 05. During the disassembly of the rig to remove bearing 06, an unscheduled grease sample was removed from bearing 05 to increase the data base. Bearing 05 failed after 91.2 MREV. To further add to the data base, a second unscheduled grease sample was removed from bearing 05 after 77.3 MREV and three grease samples were removed from bearing 09.

14. A general observation made during the inspection of the bearings was that the quantity of wear within the roller pockets of the cage was significant. That is, the amount of wear debris from the cage could possibly be appreciably greater than the debris from the other elements even when they are approaching failure. Therefore, in the analysis of the grease retained debris, care must be taken to factor out the debris from the cage as they present little information on the life state of the bearing.

B. TESTING RESULTS: The test record of all bearings is presented in Table 1, and the optical microscope examination results are presented in Appendix A.

1. Set I Bearings (No. 05 and 06)

a. The testing of Set I bearings progressed uneventfully for a period of 734 hours (35 MREV) with grease samples removed as scheduled. After 734 hours of operation a vibraswitch shutoff occurred indicating a fatigue failure. Visual inspection of the two test bearings while still assembled on the

rig showed that bearing 06 had failed. Grease samples were removed from both bearings. Bearing 06 was removed, cleaned, and inspected.

b. The surface distress in bearing 06 indicated that the lubrication had been marginal at some stage during the testing. Whether this occurred before or after the initiation of the spalls could not be determined. However, the bearing was considered failed due to the presence of the cone race spall.

c. The testing of bearing 05 was continued using bearing 09 in place of bearing 06. After 1,045 hours of additional testing for an accumulation of 91.2 MREV, the testing of bearing 05 was terminated due to a vibraswitch shutoff indicating a spall. The inspection of bearing 05 showed that a spall had occurred on the inner ring. The unspalled surface was glazed with a few microspalls, indicating the early stages of surface distress. In addition, appreciable denting resulted from the rollers passing over the spall debris.

d. To add to the data base, grease samples were removed from bearing 09 during the running and the bearing inspected when bearing 05 failed. The inspection of bearing 09, which had run for 55.6 MREV at test termination, showed appreciable glazing and some microspalling. Although there were signs of both early and advanced stages of surface distress, this bearing had not experienced a bona fide failure.

2. Set II Bearings (No. 07 and 08)

a. Both of these bearings ran to a time-up of 2,083 hours or 100 MREV. Grease samples were taken and the bearings were inspected and regreased at the scheduled 5 MREV, 25 MREV, 50 MREV, and at the termination of the test. In addition, grease samples were taken after 77.9 MREV to add to the data base.

b. The inspection of bearing 07 after 5 MREV showed that some minor surface distress had occurred, but the finish grinding lines were still present over the complete race. After 25 MREV the surface distress had increased on the inner ring. In one location in the center of the race, the very shallow microspalls (surface distress) had proliferated to cover an area of approximately 0.25 by 0.12 inch, resulting in a frosted appearance when viewed with the naked eye. When a bearing has developed the surface distress as observed in one location in this bearing, it is questionable whether it should be considered failed and therefore replaced. Surface distress is a condition resulting from borderline lubrication, and it could relatively quickly progress to a spall failure, unless a change is made to arrest its progression. Since the surface distress in this bearing appeared to be extremely shallow, and experience has shown that an improvement in the lubrication quality will often arrest surface distress progression, it was decided that the testing of bearing 07 should be continued after regreasing as scheduled. The operation of bearing 07 was continued as scheduled to a test-time-up period of 100 MREV without a bona fide failure.

TABLE 1 - TEST RECORD OF TAPERED ROLLER BEARINGS

Bearing No.	Operating Period (1 MREV)	Minimum/ Maximum Cup Temperature (°C)	Down-time (Hr)	Reason for Downtime	Grease Sample Taken	Bearing Cleaned	Bearing Inspected (Optical Micro/Sem)	SEM Photos Taken
06	0-3.6	52/58	61.5	Shut down for weekend				
	3.6-5	46/51	16	Remove grease sample	X			
	5-25	51/71	39	Remove grease sample	X			
	25-35	52/62	-	Spall failure	X	X	X/X	X
05	0-3.6	45/52	61.5	Shut down for weekend				
	3.6-5	41/56	16	Remove grease sample	X			
	5-25	46/54	39	Remove grease sample	X			
	25-35	44/55	312	Bearing 06 failed	X			
	35-50	47/58	96	Remove grease sample	X			
	50-77.3	46/59	8	Remove grease sample	X			
	77.3-91.2	49/62	--	Spall failure	X	X	X/X	X
09	0-13.9	41/59	96	Remove grease sample	X			
	13.9-41.7	47/62	8	Remove grease sample	X			
	41.7-55.6	52/61	-	Bearing 05 failed	X	X	X/X	
07	0-3.5	56/61	61.5	Shut down for weekend				
	3.5-5	54/60	384	Replace grease and inspect	X	X	X/X	X
	5-20.6	52/55	137	Test monitoring computer down				
	20.6-25	51/60	403	Replace grease and inspect	X	X	X/X	X
	25-50	49/56	147	Replace grease and inspect	X	X	X/X	X
	50-77.7	51/65	6	Remove grease sample	X			
	77.7-77.9	-	744	Test monitoring computer down				
	77.9-100	49/60	-	Test time up	X	X	X/X	X
08	0-3.5	44/55	61.5	Shut down for weekend				
	3.5-5	48/50	384	Replace grease and inspect	X	X	X/X	X
	5-20.6	43/53	137	Test monitoring computer down				
	20.6-25	40/49	403	Replace grease and inspect	X	X	X/X	X
	25-50	45/54	147	Replace grease and inspect	X	X	X/X	X
	50-77.7	42/53	6	Remove grease sample	X			
	77.7-77.9	-	744	Test monitoring computer down				
	77.9-100	51/68	-	Test time up	X	X	X/X	X

c. The progressive inspections of bearing 08 showed that the changes in surface condition of the races paralleled those of bearing 07 with the following exceptions: (1) the size of the microspalls developed between 5 MREV and 25 MREV were appreciably smaller in bearing 08 and more superficial as noted by the presence of some finish grinding lines, (2) the surface distress in bearing 08 extended over a wider area of the inner race. Neither bearing 07 nor 08 experienced a failure.

IV. DEBRIS CHARACTERISTICS

A. In general, wear particles generated by the different wear modes, exhibit various geometries that can vary depending on the type of component wearing. In the area of wear debris analysis it is important that the debris for various components be categorized such that it may be possible to isolate a specific component in a complex system by matching debris characteristics. The following describes the debris characteristics that were observed in the grease-lubricated tapered roller bearings of this experiment.

B. RUBBING WEAR. Rubbing wear particles exhibit a flake-like appearance and are the result of a benign form of wear common to boundary lubrication. The particles observed were found to have major dimension-to-width (L:W) ratios ranging from 2:1 to 5:1 with the majority being 4:1. Major dimension-to-thickness (L:Th) ratios varied from 3:1 to 8:1 with the majority in the 3:1 to 5:1 range. Overall major dimensions were found to vary from 3 um to 9 um but the majority of particles measured 4 um and 5 um. Rubbing wear was the predominant wear mode during the beginning of the test cycle (60% to 70% of the total) but diminished to lower levels (20% to 30%) as operating time increased. This pattern was typical of all bearings tested whether a failure occurred or not.

C. LAMINAR WEAR. Laminar wear is primarily found in rolling contact situations; the particles are thin, bright, free metal, having holes in their surface. The L:W ratio ranged from 3:1 to 11:1 with the majority being 6:1, while the L:Th ratio range was 3:1 to 55:1 with the majority in the 30:1 to 40:1 range. Major dimensions varied widely, 10 um to 65 um, with the majority in the 30 um to 40 um range. Laminar particle quantities exhibited trends opposite to those of rubbing, low levels (15% to 25%) at the onset of testing and increasing to levels as high as 68%.

D. Severe Wear. Particles characteristic of severe sliding wear were also observed in the samples, but to a much lesser degree than the preceding types. Typically these particles are large and irregularly shaped and do not readily form particle strings on ferrograms. L:W ratios varied from 3:1 to 10:1 with the majority being 4:1 and 5:1, and L:Th ranges were 4:1 to 20:1 with the majority at 10:1 and 15:1. Major dimensions ranged from 5 um to 40 um, but the majority were observed at 15 um to 25 um. The overall quantity of severe wear particles was low, 2% to 5%, but did increase to as high as 20%. Overall trends exhibited were similar to laminar particles, increasing in quantity with time.

E. Cutting Wear. Cutting wear particles were also in evidence. These particles resemble tiny lathe chips or coils. L:W ratios ranged from a low of 4:1 to 40:1 with the majority being 10:1 and 15:1, L:Th varied from 8:1 to 30:1 with the majority at 10:1 and 15:1. The major dimension varied from 5 um to 45 um with most of them falling in the range of 10 um to 15 um. Overall quantities rarely exceeded 5% of the total and levels remained fairly constant throughout the test period.

F. Fatigue Wear. Particles usually associated with fatigue, free metal spheres and chunks composed of free metal showing detailed crystalline faces,

were the least occurring particles. When present, the fatigue chunks possessed L:W ratios of 2:1, while the L:Th ranged from 2:1 to 6:1 with a mean of 4:1. Typically, major dimensions fell within the 6 um to 12 um range. Spheres were also found to be scarce with the maximum occurrence of 7 on any one sample and measuring 2 um to 6 um in diameter.

G. Miscellaneous Particles. Other types of particles, such as red oxides and platelets, were in evidence. These occurred very sporatically and, as such, no quantitative information was gathered.

V. FERROGRAPHIC BEARING ANALYSIS

A. Particle quantities plotted against component operating time resemble the shape of the classic "bathtub" curve of wear life. The initial rise in quantity represents the wear-in period, the ensuing decrease and leveling off represents the normal wear regime, and the increase that follows the wear-out period. Based on this it is possible to estimate these regimes by observing overall particle quantities versus time. For the purpose of this discussion, the ferrographic density readings corresponding to large particles (D54 or A_L) and to small particles (D50 or A_S) are used as an indicator of particle quantities. This criteria is applied to divide the data, from the three bearings that did not exhibit failures (Bearings 07, 08, and 09), into the major wear regimes. The data from the remaining bearings (Bearings 05 and 06) are reported by sampling periods.

B. BEARING 07. Testing of this bearing was terminated at 100 MREV without reaching the wear-out regime. Samples from the wear-in and normal-wear periods were analyzed with the following results:

TABLE 2 - BEARING 07 SAMPLING RESULTS

		WEAR-IN PERIOD				NORMAL WEAR PERIOD					
		Quantity (%)		Major Dimen. (μm)		Quantity (%)			Major Dimension (μm)		
		MREV		MREV		MREV			MREV		
Sampling Location	Type Wear	5	25	5	25	50	77.7	100	50	77.7	100
Inboard	Rubbing	55	50	9	4	35	30	30	4	4	4
	Laminar	30	20	50	30	55	55	60	40	40	50
	Severe	9	5	40	20	5	8	10	20	20	8
	Fatigue	5	0	6	0	0	0	0	-	8	-
	Cutting	1	10	30	15	5	5	-	15	10	-
	Spheres (4)	-	-	-	-	-	-	-	-	5	-
Outboard	Rubbing	70	75	7	4	60	40	40	4	4	5
	Laminar	15	15	40	10	40	50	50	18	30	35
	Severe	9	5	35	-	0	10	10	-	15	15
	Cutting	1	0	20	0	0	0	0	-	-	-

1. INBOARD SAMPLING LOCATION

a. Wear-In. Based on the previous criteria, wear-in took place during the first 25 MREV of operation. During this time all five of the major wear modes were represented in the sample. Rubbing wear was the primary mode making up the majority, followed by laminar and then severe and fatigue wear; the quantity and size of these items decreased by the 25 MREV point. Cutting wear also present, increased during wear-in, while reducing in size. Temper particles were also noticed during this period.

b. Normal Wear. The normal wear region occurs in the 25 MREV to 100 MREV operating range. During this period, the quantity of rubbing particles dropped while laminar debris increasd. Rubbing wear fell at 77.7 MREV and then remained constant to the end of the period, while the size remained constant throughout. Laminar debris increased in quantity from a low of 20% to a high of 60%; its size also increased. Severe wear quantities varied, while the size remained constant and then dropped at 100 MREV. Cutting wear dropped in quantity, with none evident in the final sample. Fatigue did not reappear until after 77.7 MREV. Four spheres measuring 2 to 5 μm were noticed at 77.7 MREV.

c. Wear-Out. Testing was terminated at 100 MREV; therefore, no data is available to report for wear-out.

2. OUTBOARD SAMPLING LOCATION

a. Wear-In. Based on outboard data, the wear-in period occurred between 5 and 25 MREV, possibly closer to the 5 MREV point. Rubbing wear levels, again predominant, were somewhat higher than the inboard samples, while sizes were similar. Laminar particle quantities and sizes were less than those recorded for inboard samples. Severe and cutting wear at 5 MREV showed the same quantities as the inboard samples. Cutting wear was not present at 25 MREV. Temper was also noticed during this period.

b. Normal Wear. During the same period as the inboard location, the outboard samples exhibited similar trends for rubbing and laminar wear except levels were higher by 10 percentage points. Size wise, the rubbing particles were the same while the laminar were 50% smaller. There was no evidence of fatigue or cutting wear, while severe wear increased at 77.7 and 100 MREV.

c. Wear-Out. No data available due to test termination.

3. ACTUAL BEARING CONDITION

a. During the wear-in period, the following surface conditions were observed. At 5 MREV the inner ring (cone) and outer ring (cup) were in relatively good condition, with finish marks still evident, except for some microspalling distributed over the surfaces. The rollers were in excellent condition with no wear evident, other than a slight poliching on the large end due to contact with the inner ring flange. Appreciable wear was evident in the roller pockets of the cage, primarily on the inside surface of the minor diameter rail. At 25 MREV the cone experienced a slight increase in microspalling, while the cup remained unchanged. There was no observable change in the roller, though cage wear persisted.

b. No change in actual condition was observed at 50 MREV with minor wear continuing in the cage portion. At 100 MREV the inner ring surfaces exhibited an approximate 50% increase in microspalling with no major spalls or cracks apparent. The outter ring showed no change while four of the rollers showed signs of microspalling.

4. Quantitative Data: The primary quantitative data available from a ferrographic analysis are density readings, specifically those taken at the D54 location corresponding to large debris and those at the D50 location corresponding to small debris. These readings are denoted A_L and A_S respectively. From these two readings, three parameters indicative of wear can be obtained. These parameters are the overall quantity ($A_L + A_S$), severity of wear ($A^2_L - A^2_S = S_A$), and an indicator of abnormality ($A_L - A_S$). Table 3 summarizes these parameters for both the inboard and outboard locations of bearing 07.

TABLE 3

SUMMARY OF DENSITIES AND RELATED DATA FOR BEARING 07

	(MREV)	5	25	50	77	100
INBOARD	A_L	-	4416	2392	448	896
	A_S	-	2920	2232	388	792
	$A_L + A_S$	-	7336	4624	836	1688
	$A_L - A_S$	-	1496	160	60	104
	S_A (10^6)	-	11	0.74	0.05	0.18
OUTBOARD	A_L	-	416	552	756	4288
	A_S	-	256	368	368	2784
	$A_L + A_S$	-	672	920	1124	7072
	$A_L - A_S$	-	160	184	388	1504
	S_A (10^6)	-	0.11	0.17	0.44	11

C. BEARING 08. Testing of this bearing was terminated at 100 MREV without reaching the wear-out regime. Samples from the wear-in and normal-wear periods were analyzed with the following results:

TABLE 4 - BEARING 08 SAMPLING RESULTS

Sampling Location	Type Wear	WEAR-IN PERIOD Quantity (%) MREV 5	25	Major Dimen. (µm) MREV 5	25	NORMAL WEAR PERIOD Quantity (%) MREV 50	77.7	100	Major Dimension (µm) MREV 50	77.7	100
Inboard	Rubbing	50	40	6	3	35	30	30	4	4	3
	Laminar	30	40	45	30	55	55	55	35	30	40
	Severe	10	13	40	20	8	12	10	10	30	25
	Cutting	10	4	40	10	2	3	5	6	15	15
	Fatigue	-	3	-	8	-	-	-	-	-	-
Outboard	Rubbing	45	40	8	5	30	30	35	4	4	5
	Laminar	33	40	50	30	50	60	55	25	35	40
	Severe	13	10	40	25	15	8	6	15	20	20
	Cutting	7	8	45	30	5	2	2	15	10	15
	Fatigue	2	2	10	8	1	-	2	6	-	8
	Spheres (2-7)	-	-	-	-	-	-	-	5	6	-

1. INBOARD SAMPLING LOCATION

a. Wear-In. As before, wear-in took place during the first 25 MREV of operation. Rubbing wear dominated the first 5 MREV, followed by laminar, then severe and cutting wear. Fatigue particles were not observed. As wear-in continued to 25 MREV, rubbing and cutting wear decreased while laminar and severe wear increased. Fatigue became evident during the last 20 MREV.

b. Normal Wear. The normal wear regime began just after 25 MREV and ran to 100 MREV where transition to wear-out occurs. The dominant wear particle switched to laminar, followed by rubbing debris, severe, and cutting wear. Throughout the normal wear period, laminar wear remained dominant and stable, while rubbing wear decreased; severe wear increased slightly in quantity and size and then decreased; cutting increased in quantity and major dimensions. No fatigue particles were observed.

2. OUTBOARD SAMPLING LOCATION

a. Wear-In. During the first 5 MREV of wear-in, the particle distribution was similar to that of the inboard sampling locations, with rubbing wear again dominant, followed by laminar, severe, and cutting wear. Fatigue particles were present. At the next sampling point, the particle distribution was similar to the corresponding inboard sample: rubbing and severe wear decreased, laminar and cutting debris quantity increased and size decreased, while fatigue slightly decreased in size.

b. Normal Wear. In general this location reflected a similar distribution as the corresponding inboard sample with the exception of variations in major dimension. The following statements use the 50-MREV sample data as a basis for comparison. Laminar debris dominated throughout this period; the quantity increased then decreased, and size increased. Rubbing followed—it increased in quantity and slightly in size. Severe and cutting wear were somewhat higher than the inboard values; both increased in quantity, while severe wear increased in size. Fatigue particles were present in the 50- and 100-MREV samples. Spherical particles were found in the 50- and 77.7-MREV samples: 2 to 5 at 5 μm and 2 to 7 at 6 μm respectively.

3. ACTUAL BEARING CONDITION

a. During wear-in, inspection of the bearing found the inner race to be in excellent condition with some minor dents present and the back faced rib to be polished. The outer race was also in excellent condition with some fretting on the outside diameter. Rollers were also excellent with the larger end polished. The cage sustained appreciable wear on the inside minor diameter. At the conclusion of wear-in, the inner race degraded in appearance having four distinct circumferential bands of surface distress, ranging from minor distress at the outboard to glazing and microspalling at the inboard. The outer race condition was similar to the inner race with no microspalling evident. The rollers were discolored and the cage exhibited uniform wear.

b. The inspection at 50 MREV showed little change in the races except for a slight increase in the number of dents in the outer race. The cage portion continued uniform wear and exhibited a higher polish. Final inspection at test termination revealed an increase in cable wear scars with no changes in the remainder of the bearing.

4. QUANTITATIVE DATA. Table 5 summarizes the data for bearing 08 as defined in paragraph VB4.

TABLE 5 - SUMMARY OF DENSITIES AND RELATED DATA
FOR BEARING 08

	(MREV)	5	25	50	77	100
INBOARD	A_L	-	1012	195	51	420
	A_S	-	848	67	13	204
	$A_L + A_S$	-	1860	262	64	624
	$A_L - A_S$	-	164	128	38	216
	S_A (10^6)	-	0.3	0.03	0.002	0.13
OUTBOARD	A_L	-	5636	19	40	468
	A_S	-	4256	14	40	324
	$A_L + A_S$	-	9942	33	80	792
	$A_L - A_S$	-	1380	5	0	144
	S_A (10^6)	-	14	0	0	0.11

D. BEARING 09. This bearing was installed in place of Bearing 06 which failed prematurely at 35.6 MREV. Samples were taken at 13.9, 41.7, and 55.6 MREV as shown in Table 6.

TABLE 6 - BEARING 09 SAMPLING RESULTS

Sampling Location	Type Wear	Quantity (%)/Major Dimension (µm) MREV 13.9	41.7	55.6
Inboard	Rubbing	50/ 5	40/ 4	30/ 4
	Laminar	35/ 20	45/ 30	50/ 40
	Severe	10/ 20	10/ 25	16/ 30
	Cutting	5/ 15	5/ 15	2/ 15
	Fatigue	0/ 0	0/ 0	2/ 8
Outboard	Rubbing	55/ 4	40/ 4	25/ 5
	Laminar	40/ 25	50/ 35	65/ 45
	Severe	2/ 16	5/ 28	7/ 30
	Cutting	3/ 15	5/ 20	3/ 15
	Fatigue	0/ 0	0/ 0	0/ 0

1. INBOARD SAMPLING LOCATION. Rubbing wear was dominant in the first sample, and became subordinate to laminar wear in the second and third samples. Severe wear increased in size in second and third samples, and in dimension in the third sample. Fatigue became evident in the last sample.

2. OUTBOARD SAMPLING LOCATION. Again Rubbing wear was dominant in the first sample. Laminar wear increased in quantity and size in second and third samples, and became the dominant factor. Severe wear increased in each sample. Cutting showed a slight increase in the second sample. Fatigue wear was not evident in any of the samples.

3. ACTUAL BEARING CONDITION. The bearing was disassembled and inspected at the end of the test, 55.6 MREV. The inner race was in relatively good condition with some microspalls at the center. The outer race was in a similar state with some microspalls at the minor diameter and a 90-degree segment in the radial load zone. The cage exhibited minimal wear while the rollers were in good condition.

4. QUANTITATIVE DATA: Table 7 is a summary of the quantitative data for bearing as defined in paragraph VB4.

TABLE 7

SUMMARY OF DENSITIES AND RELATED DATA FOR BEARING 09

	(MREV)	13.9	41.7	55.6
INBOARD	A_L	432	828	280
	A_S	264	324	172
	$A_L + A_S$	696	1152	452
	$A_L - A_S$	168	504	108
	S_A (10^6)	0.12	0.58	0.049
OUTBOARD	A_L	139	152	620
	A_S	75	109	148
	$A_L + A_S$	214	261	768
	$A_L - A_S$	64	43	472
	S_A (10^6)	0.013	0.011	0.36

E. BEARING 05. Bearing 05 failed at 91.2 MREV. The following Table lists the ferrographic data obtained through the bearing's life. These data are not divided into the various wear regimes as previously described, but are summarized for each of the sampling locations.

TABLE 8 - BEARING 05 SAMPLING RESULTS

Sampling Location	Type Wear	Quantity (%)/Major Dimension (μm) MREV 5	25	35	50	77	91.2*
Inboard	Rubbing	65/ 4	70/ 4	55/ 5	35/ 6	-	35/ 5
	Laminar	25/ 25	25/ 36	30/ 40	51/ 30	-	40/ 50
	Severe	2/ 12	5/ 27	10/ 30	5/ 12	-	15/ 25
	Cutting	4/ 8	0/ 0	3/ 30	3/ 10	-	5/ 20
	Fatigue	0/ 0	0/ 0	2/ 6	6/ 8	-	5/ 12
Outboard	Rubbing	60/ 4	40/ 5	35/ 5	30/ 4	35/ 4	27/ 4
	Laminar	30/ 30	55/ 15	50/ 30	60/ 30	60/ 45	68/ 55
	Severe	4/ 10	5/ 25	10/ 27	5/ 18	5/ 20	5/ 16
	Cutting	4/ 10	0/ 0	2/ 16	5/ 18	0/ 0	0/ 0
	Fatigue	0/ 0	0/ 0	2/ 6	0/ 0	0/ 0	0/ 0

* Failure

1. INBOARD SAMPLING LOCATION. Rubbing wear was dominant until the 50-MREV sample where laminar wear took the lead. Severe wear increased until 50 MREV where it dropped, and then increased in the 91.2-MREV sample. Cutting wear was not evident in the 25-MREV sample, but remained quite stable in quantity and varied in size in other samples. Fatigue became evident in 35 MREV sample and increased thereafter.

2. OUTBOARD SAMPLING LOCATION. Rubbing wear dominated only the 5-MREV sample; laminar debris dominated thereafter. Severe wear was quite stable except for the 35-MREV sample which produced greated quantity and size; the size varied in other samples. Cutting wear was sporadic and varied, while fatigue wear was found only in the 35-MREV sample.

3. ACTUAL BEARING CONDITION. Upon disassembly, after failure, the following bearing condition was observed. The inner race was glazed and microspalls covered the full circumference. The outer race also exhibited microspalling in a 90-degree segment of the minor diameter in the radial load zone. The cage exhibited a minimum amount of wear, while the rollers showed no signs of distress.

4. QUANTITATIVE DATA. Table 9 summarizes the particle quantities, as defined in paragraph VB4, based on normalized ferrogram density readings and the computed severity of wear index (S_A).

TABLE 9

SUMMARY OF DENSITIES AND RELATED DATA FOR BEARING 05

	(MREV)	5	25	35.6	50	77.3	91.2
INBOARD	A_L	-	2672	376	3424	2424	4768
	A_S	1112	3160	1360	2744	1664	3464
	$A_L + A_S$	-	5832	1736	6168	4088	9536
	$A_L - A_S$	-	-488	-984	680	760	1304
	S_A (10^6)	-	-2.8	-1.7	4.2	3.1	12.4
OUTBOARD	A_L	-	1532	1064	1496	2232	1336
	A_S	225	936	652	1128	1760	984
	$A_L + A_S$	-	2468	1716	2624	3992	2320
	$A_L - A_S$	-	596	412	368	472	352
	S_A (10^6)	-	1.5	0.71	0.96	1.9	0.82

F. <u>BEARING 06</u>. This bearing failed prematurely at 35.6 MREV. Samples were taken at 5, 25, and 35.6 MREV as shown in Table 10.

TABLE 10 - BEARING 06 SAMPLING RESULTS

Sampling Location	Type Wear	Quantity (%)/Major Dimension (μm) MREV 5	25	35.6*
Inboard	Rubbing	60/ 7	30/ 5	30/ 4
	Laminar	30/30	40/40	45/30
	Severe	8/24	19/35	10/25
	Cutting	2/ 8	5/30	2/10
	Fatigue	0/ 0	5/ 8	10/10
	Spheres	-	0/ 7	0/ 7**
Outboard	Rubbing	60/ 5	30/ 5	30/ 4
	Laminar	30/35	45/40	45/45
	Severe	5/25	15/35	15/40
	Cutting	5/15	5/25	5/20
	Fatigue	0/ 0	5/10	5/10

* Failure
** No. of spheres (several) tripled.

1. INBOARD SAMPLING LOCATION. Rubbing was dominant in the first sample, but was dropped to second place by laminar wear in the second and third samples. Also present were severe and cutting wear, both of which increased then decreased in the second and third samples respectively. Fatigue, evident only in the second and third samples, increased in the last sample. Several 2- to 7-um spheres were found in the second sample; the number of spheres tripled in the third sample.

2. OUTBOARD SAMPLING LOCATION. Again laminar wear surpassed rubbing wear in the second and third samples. These were followed by severe and cutting wear. Fatigue was evident only in the second and third samples.

3. ACTUAL BEARING CONDITION. The inner race was spalled at depths ranging from 0.003-inch to 0.015-inch with other areas glazed--this indicates early stages of surface distress. The outer race and rollers were heavily dented, although no spalling was evident. The cage experienced minor wear.

4. QUANTITATIVE DATA. Table 11 is a summary of the quantitative data available from bearing 06, as defined in paragraph VB4.

TABLE 11 - SUMMARY OF THE DENSITIES AND RELATED DATA FOR BEARING 06

	(MREV)	5	25	35.6
INBOARD	A_L	-	1044	532
	A_S	56	368	1528
	$A_L + A_S$	-	1412	2060
	$A_L - A_S$	-	676	-996
	S_A (10^6)	-	0.95	-2.05
OUTBOARD	A_L	-	1776	1672
	A_S	64	1184	1680
	$A_L + A_S$	-	2960	3352
	$A_L - A_S$	-	592	-8
	S_A (10^6)	-	1.8	-0.027

VI. DISCUSSION OF DEBRIS ANALYSIS

A. SAMPLING LOCATION

1. One objective of this effort was to establish the optimal sampling location for determining the wear state of the component. All grease samples were obtained from the inboard and outboard locations of the bearing's cage/roller assembly, as positioned in the test apparatus (Figure 1). This was due to the lack of sufficient quantities of grease available at other locations. The types of debris were the same on either side of the bearings, although fatigue particles were found to be more prevalent at the outboard location. Particle quantities, on the other hand, were found to vary between locations. Some variation is to be expected due to the geometry of the bearing, which tends to cause debris migration away from the minor diameter (outboard) toward the inboard side. This was illustrated by the data, in that quantities of debris were found to be higher for the inboard location. However, there were instances of excessively high quantities of debris at the outboard locations occurring at the beginning of the operating cycle. This condition appears to be due to the excessive wear of the cage portion.

2. Due to these variations between inboard and outboard locations, it is best to analyze samples from both locations, thus forming a better picture as to the wear state of the component.

B. RELATIONSHIP BETWEEN QUALITATIVE DEBRIS INFORMATION AND SURFACE CONDITION.

1. FATIGUE PARTICLES

a. An important aspect in the application of wear debris analysis, to the prediction of component wear state, is the relationship between the debris morphology and the actual condition of the component. In the case of tapered roller bearings, whose primary mode of failure is fatigue, it is of particular interest to ascertain the presence of debris related to this failure mode. Typically, the wear debris associated with fatigue are fatigue chunks, laminar particles, and spheres.

b. Fatigue particles appeared, at one time or another, during the tests in all of the bearings. Fatigue particles, also referred to as chunks, constitute the actual material removed as a pit or a spall during the process of surface fatigue. In most cases a direct correlation exists between the appearance of fatigue particles and actual spalling of the bearing surface. Bearings 05 and 06 both had spalled races upon examination at the end of their respective run times. In each instance fatigue particles were first observed at 35 MREV and 25 MREV respectively. Variations were noticed between samples taken from the same bearing; in bearing 05 the outboard sample showed fatigue only at the 35 MREV time, while the inboard sample contained fatigue at 35

through 91.2 MREV. This situation also existed in bearings 08 and 09. The outboard location of bearing 08 showed evidence of fatigue throughout its life except for the 77.7-MREV point, while the inboard location showed evidence of fatigue chunks only at the 25-MREV point. Bearing 09 analysis revealed no fatigue at the outboard location while a trace was observed inboard at 55.6 MREV (test termination). Bearing 07 showed indications of fatigue during wear-in for both the particle and surfact analysis at 5 MREV, but at the next sampling point the surface analysis indicated an increase in spalling with no indications in the debris analysis.

c. Based on fatigue particles, abnormalities are typically indicated by increasing quantities of particles larger than 10 μm, with particles increasing to 100 μm during microspalling and continuing to increase in size until failure occurs. None of the bearings produced fatigue particles in excess of 12 μm which only bearing 05 produced, as observed at the inboard location at 91.2 MREV, the point of failure. However, the expected increase in quantity did not occur. Bearing 06, which experienced a premature failure at 35 MREV, had a maximum particle size of 10 μm. Particle quantities did increase based on the inboard sample as did size, but remained constant in both size and quantity at the outboard location. Of the bearings that exhibited no failure, quantities of fatigue particles never exceeded the 10% of the total debris quantity observed in isolated cases. Typically, quantities remained at levels below 1 or 2% during the bearing life.

d. Although, in most cases, the appearance of fatigue particles did coincide with spalling of the bearing surface, taken alone they are not shown to be a good indicator of impending failure.

2. LAMINAR PARTICLES

a. Another particle type usually associated with rolling element fatigue is the laminar particle. Laminar particles are very thin, free metal particles thought to be formed by the passage of other forms of debris, through rolling contact after adhering to a rolling element.

b. At a glance there are no differences in particle size and quantity trends between bearings that exhibited failure and those that didn't.

Typically, laminar debris quantities increased with operating time while no clear trends exist for sizes, which did tend to fluctuate during the bearing's life.

c. Quantities of laminar particles have been found to increase at the onset of fatigue spalling. This was not found to be the case during these tests. Although an increase was noted at times when spalling was present, instances exist where laminar quantities continued to increase without a noticeable increase in spalling. As an example, bearing 07's outboard sample exhibited a slight increase in debris quantity between 5 MREV and 25 MREV with an increase in microspalling. Subsequent samples exhibited continued growth in debris quantities without a noticeable increase in surface fatigue.

d. The results obtained during this investigation as related to the usefulness of laminar particles as an indicator of impending failure, can at best, be considered inconclusive. Expected trends for quantities were not corroborated.

3. SPHERICAL PARTICLES

a. The last form of particle associated with rolling element fatigue is the sphere. Spherical particles, if generated, give an improved warning of impending trouble as they are usually detected prior to the actual spalling. It should also be noted that the absence of spheres does not rule out the possibility of fatigue.

b. Examination of the ferrograms during the test program did reveal spherical particles at various times, for three of the test bearings, one of which failed. Where periodic disassembly occurred and direct comparison between particle results and actual condition could be made, one instance, bearing 07, inboard location did exhibit spheres prior to a later increase in microspalling. Bearing 08, outboard sample, exhibited spheres in two consecutive samples, 50 MREV and 77.7 MREV, without a corresponding increase in spalling. Prior spalling had occurred so that these spheres may have been produced by existing cracks which had not had time to propagate into spalls before test termination at 100 MREV. In the remaining bearing, 06 had spheres present in the analysis with fatigue spalls in evidence at final inspection, while bearing 09 did not produce spheres but did experience some fatigue. These results do tend to support the results of other studies concerning the relationship of spherical particles and surface fatigue.

4. SEVERE AND CUTTING WEAR

a. Two other particle types that are associated with undesirable wear, severe and cutting, were also observed.

b. In most cases the sliding wear was attributed to the interaction between the roller and cage. This is supported by the fact that instances of larger quantities, up to 10%, of severe wear were found to correspond with appreciable wear in the cage.

c. The origin of the cutting debris is unknown, but it is believed that the debris is actually finish lines that have delaminated from the surface.

5. Based on this investigation, it is felt that fatigue particles and spheres will provide the most useful qualitative information on the surface condition of the bearing. Due to the limited sample involved it was not possible to determine the prognostic capabilities of this information as there were no substantial trends noticeable.

C. QUANTITATIVE DEBRIS INFORMATION

1. As stated earlier in this report, three wear parameters are derived from the two basic density readings that are representative of large and small debris. These are the overall quantity, the sum of the two readings; the severity of wear, the difference between the square of the large reading and the square of the small reading; and an indicator of abnormality, the larger reading less the smaller reading.

2. The density readings were found to be variable. Substantial variations were found between samples at neighboring intervals with no substantial change in the wear condition in evidence. Density readings taken at identical intervals but different locations yielded in most cases, extreme variations. Some variations being as much as an order of magnitude. Although a difference is expected, due to bearing geometry, the variations exhibited are too high in most cases to be useful. A previous study dealing with ferrographic analysis of grease found that a substantial amount of organic material is left on the slide which has an adverse effect on the density readings. This could explain the variations of the density readings obtained and would make the quantitative data unusable for comparative purposes between bearings.

3. Since the remaining parameters are all derived from the two basic density readings, they are not considered to be usable because of the questionable validity of the readings. Based on this, a quantitative assessment as to the severity of wear taking place and current condition of the bearing could not be made.

VII. CONCLUSIONS

A. The use of both the inboard and outboard sampling locations is considered to be required in order to obtain an accurate picture of wear modes present.

B. Morphological data is considered to be the most accurate indicator of abnormalities. A distinct correlation was made between the various debris morphologies and the failure modes exhibited by the bearings.

C. Quantitative data did not exhibit good correlation in predicting abnormal wear. This is primarily due to the films left by the greases on the ferrograms which tend to distort the optical measurements of the ferrograph. Another factor is the nature of grease precludes a uniform dispersion of the debris within the grease.

D. Due to the inconsistencies in obtaining representative samples, the monitoring of grease-lubricated components would not be practical in a maintenance environment.

APPENDIX A

OPTICAL MICROSCOPE OBSERVATIONS OF TEST BEARINGS

OPTICAL MICROSCOPE OBSERVATIONS OF TEST

BEARING NO. 05 FOLLOWING TEST

Bearing 05 after 1,879 hours or 91.2 MREV

Inner Ring (Cone)

A total of seven spalls had occurred with the largest spall approximately 3/16 inches long and extending the full width of the race from which many pieces had exfoliated. All spalls were quite shallow with the deepest being approximately 0.015 inch and the rest varying from .003 to .10 inch. The unspalled surface of the face was highly glazed, indicating early stages of surface distress with a uniform distribution of large (0.1 inch) and small (0.002 inch) dents. An amber discoloration band approximately 5/32 inch wide extended around the full circumference in the middle of the race.

Outer Ring (Cup)

One extended spall approximately 1-1/4 inches long and the full width of the race. The deepest portion of the spall was approximately 0.020 inch with the major area being 0.003 to 0.010 inch deep. The remaining portion of the race was glazed and heavily dented.

Cage

Minor wear in roller pockets. Appreciably less wear than in the cages of bearings C7 and 08 after only 5 MREV. The wear was primarily on the inside surfaces of the rails and at the intersection of the bars and rails.

Rollers

All rollers were heavily dented over roller surface with amber discoloration band matching that on cone.

OPTICAL MICROSCOPE OBSERVATION OF TEST BEARING NO. 06 FOLLOWING TEST

Bearing 06 after 730 hours or 35 MREV

Inner Ring (Cone)

A total of five spalls had occurred, with the largest being approximately 1/8 inch long and extending the full width of the race. The depth of the spalls varied from 0.003 to 0.015 inch. The unspalled surface of the race was glazed, indicating early stages of surface distress with a uniform distribution of large (approximately 0.080 inch) and small (0.002 inch) dents. The dents obviously resulted from the rollers passing over the spalled out material.

Outer Ring (Cup)

Total race surface glazed and heavily dented.

Cage

Very minor wear. Essentially no indication of wear on large diameter rail and only minor wear in two pockets on small diameter rail.

Rollers

All rollers heavily dented.

OPTICAL MICROSCOPE OBSERVATIONS OF TEST BEARING NO. 07 AT SPECIFIED INTERVALS

1. Bearing 07 after 104 hours or 5 MREV

Inner Ring (Cone)

Race in good condition with faint finish grinding marks covering complete surface. However, some slight glazing was present with a few microspalls uniformly distributed, indicating that poor lubrication existed during some portion of the run.

Outer Ring (Cup)

Race in good condition with very few microspalls. Finish lines still present even in heaviest loaded area. Small amount of fretting corrosion on outer diameter.

Cage

Appreciable wear had occurred in the roller pockets. The most wear occurred on the inside surface of the minor diameter rail and at the interface of the rails and bars where the roller makes contact.

Rollers

Excellent condition with the large end highly polished where it makes contact with the inner ring flange. No indication of wear on any other surface.

2. Bearing 07 after 521 hours or 25 MREV

Inner Ring (Cone)

Surface distress over complete width of race as noted by glazing and the increase of the microspalls. In one location the very shallow microspalls covered an area approximately 0.25 by 0.12 inch, resulting in a frosted appearance. This condition indicates inadequate lubrication at some period during the second portion of the test.

Outer Ring (Cup)

Surface in good condition with minor surface distress on portions of the race. Finish grinding lines still present over major portion of race surface.

Cage

Wear continued to occur inside roller pockets with metal flakes present on the worn surface.

Rollers

Excellent condition with no observable change.

3. Bearing 07 after 1,042 hours or 50 MREV

Inner Ring (Cone)

No appreciable change since last inspection. Microspalled areas have not increased in size and the asperities within the large microspalled area have plastically flowed to produce a smoother appearing surface.

Outer Ring (Cup)

No observable change since last inspection.

Cage

Minor wear continued as indicated by the increase in the size of the wear scars and presence of new metal flakes.

Roller

No observable change.

4. Bearing 07 after 2,083 hours or 100 MREV

Inner Ring (Cone)

The race surface areas covered by microspalls had increased approximately 50%; however, no major spalls or cracks had developed.

Outer Ring (Cup)

Race surface in good condition with minor surface distress. No observable change since last inspection.

Cage

Minor wear continued as indicated by the increase in the size of the wear scars and the presence of new metal flakes;

Rollers

Four rollers have microspalls with small areas approximately 0.020 x 0.020 inch formed by the microspalls running together.

OPTICAL MICROSCOPE OBSERVATIONS OF TEST BEARING NO. 08 AT SPECIFIED INTERVALS

1. Bearing 08 after 104 hours or 5 MREV

Inner Ring (Cone)

Race in excellent condition. Finish grinding lines observable over complete track. Several minor dents about 0.05 mm in diameter. Face of flange highly polished as expected where end of rollers make contact.

Outer Ring (Cup)

Race in excellent condition. Finish grinding lines observable over complete track. Small amount of fretting corrosion on OD surface in radial load zone.

Cage

Appreciable wear had occurred in the roller pockets. The most wear occurred on the inside surface of the minor diameter rail and at the interface of the rails and bars.

Rollers

Excellent condition with the large end highly polished where it makes contact with the inner ring flange. No indication of wear on any other surface of the rollers.

2. Bearing 08 after 521 hours or 25 MREV

Inner Ring (Cone)

General appearance of race relatively poor. Four circumferential bands were prominent on the race due to different surface distress conditions. Starting at the minor diameter: Band 1 - minor surface distress, finish grinding lines still present; Band 2 - initial stages of surface distress, highly glazed; Band 3 - very fine mottled appearance; Band 4 - surface distressed with areas varying from glazed to minor microspalls, microspalls covered approximately 7% of the band.

Outer Ring (Cup)

Banding in load zone very similar to that on inner ring except no microspalling had occurred.

Cage

Very uniform wear in all cage pockets at end of pockets on rail at rail bar interface.

Rollers

Only observable change from prior inspection was slight discoloration.

3. Bearing 08 after 1,042 hours or 50 MREV

Inner Ring (Cone)

No observable change since last inspection. Surface distress does not appear to have worsened.

Outer Ring (Cup)

No observable change except approximately 40 shallow dents occurred mostly in the center of the race.

Cage

Appears very similar to condition in prior inspection except wear areas are more highly polished. Wear flakes still attached to rails (not as many as in Bearing 07 after 50 MREV).

Rollers

No observable change since last inspection.

4. Bearing 08 after 2,083 hours or 100 MREV

Inner Ring (Cone)

No observable change since last inspection.

Outer Ring (Cup)

No observable change since last inspection.

Cage

Only slight increase in size of wear scars. Metal flakes adhering to inside of cage pocket.

Rollers

No appreciable change since last inspection.

OPTICAL MICROSCOPE OBSERVATIONS OF TEST BEARING NO. 09 FOLLOWING TEST

Bearing 09 after 1,145 hours or 55.6 MREV

Inner Ring (Cone)

Race highly glazed with all finish grinding lines essentially removed. Microspalls in 5/32-inch-wide band located in the center of race and covering the full circumference of the ring. Flange faces polished but in good condition.

Outer Ring (Cup)

Race glazed over complete surface with microspalls located at edge of race on smaller diameter in a 90-degree segment centered under the radial load zone.

Cage

Very minimal wear with only a few lightly polished areas in three pockets.

Rollers

Excellent condition with the large end polished where it makes contact with inner ring flange. No indication of wear on any other surface.

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